

Tube-Based Crossovers

with a free designer program

By John R. Broskie

crvquestion@glass-ware.com

Unless a loudspeaker uses a single full-range driver, a crossover will be needed to split up the audio spectrum into discrete bands of frequencies. But should the crossover accomplish this task passively or actively? And if actively, with solid-state devices or with vacuum tubes?

Warning.

Some of the voltages used in these circuits are potentially lethal. All relevant safety precautions should be taken to avoid any contact with any point in these circuits while they are in operation.

Please Note.

This project has not been tested or post-engineered by the *Elektor Electronics* design laboratory.

By applying two or more filters to the input signal, crossovers give each loudspeaker driver its own band of frequencies in which to operate. The filters used come in two fundamental types: digital and analogue, with the latter further subdividing into either passive or active.

Each style of filter has its advantages and disadvantages. At extremely high frequencies, where active devices become bandwidth limited, passive filters work best.

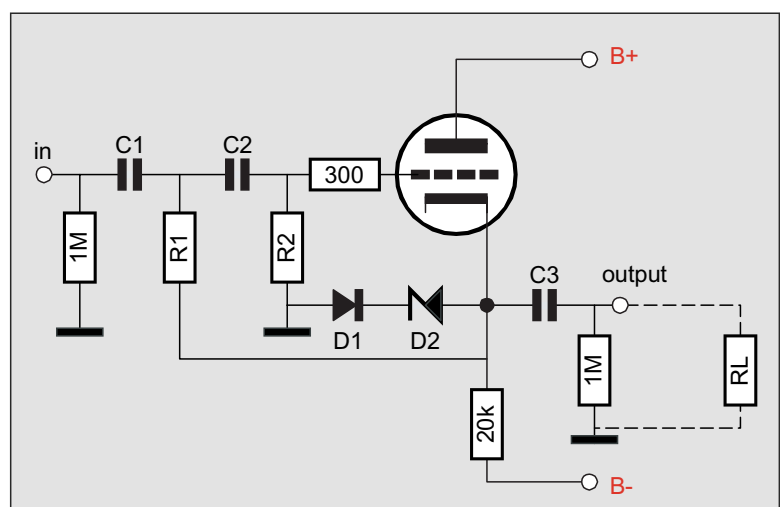
At audio frequencies, however, the active filter wins, as passive filters bring too many liabilities to the job. For example, loudspeakers use passive crossovers that hold a combination of either heavy, expensive inductors along with expensive, bulky, film capacitors; or small, inexpensive, easily saturated, and poor-tolerance inductors and

cheap, low-quality electrolytics placed in series to cancel their polarization.

Adding to these negatives, a loudspeaker's passive crossover must be tweaked to work correctly when working into the reactive load that the loudspeaker drivers present.

Active crossovers, on the other hand, forgo using inductors; instead,

they rely on inexpensive, yet precise, resistors and small, relatively inexpensive tight-tolerance capacitors to set the crossover frequencies. Beyond the savings in cost, active crossovers offer a greater accuracy and a much improved flexibility over passive crossovers. Tight-tolerance resistors and capacitors are inexpensively obtainable and are easily



0200324 - 11

Figure 1. Example of a circuit generated by the Tube Crossover Designer software. Note the use of a symmetrical supply voltage. Part values depend on your requirements, and are shown by the program along with this diagram.

swapped for different values, allowing easy changes in crossover frequency. Finally, the active crossover allows a more efficient use of the power amplifier's output, as power-wasting speaker attenuator networks are not needed, when the gain can be reduced efficiently by the mere twist of a potentiometer.

Tube-Based Crossovers

Tube-based crossovers perform the same function as solid-state crossovers, but use tubes rather than the ubiquitous IC. Why bother with tube-based audio equipment? As they say, if you have to ask, then you haven't listened to a good tube-based audio system. In an active crossover, the tube delivers the same easy-on-the-ear sound it brings to guitar amplifiers and phono preamps.

While realizing a tube-based crossover is no more difficult or complex than the solid-state alternative, it is more expensive. Tubes run on comparatively high voltages, which require comparatively higher prices. For example, a 250-volt 47- μ F capacitor costs eight times more than the 25-volt equivalent. In addition, the tubes themselves are not cheap, as a handful of ICs can be had for the same price as one good tube, definitely not the cheapest choice. Although tube gear is not easy on the wallet, it is easy on the ears and

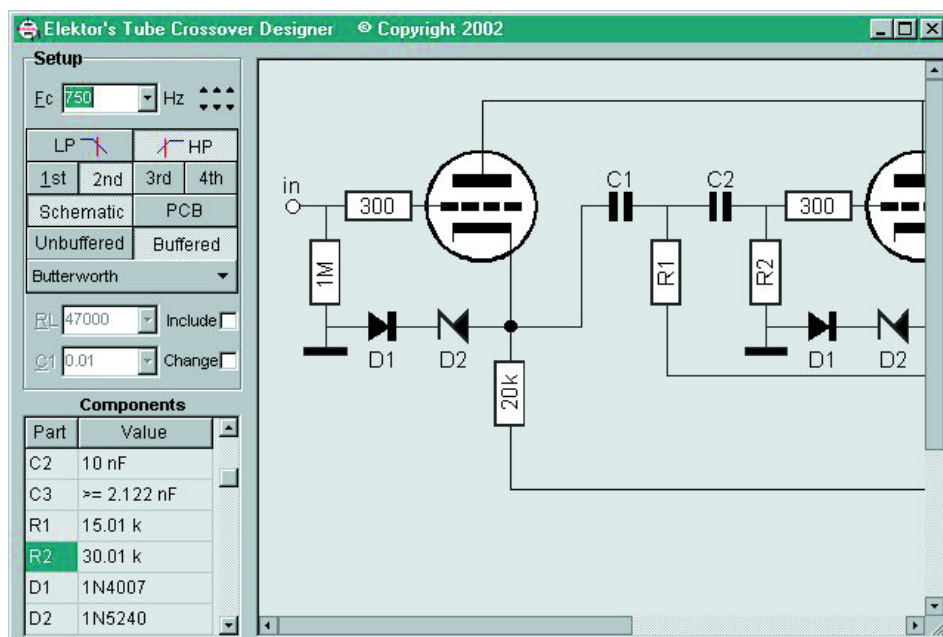


Figure 2. Elektor's Tube Crossover Designer in action. Complete circuits, parts lists and component overlays are produced at the flick of a switch.

eyes. Even when not turned on, tube gear compels attention that no IC-based equipment can match.

The Plan

This project aims to deliver a tube-based crossover in its most flexible form. Surprisingly, using a printed circuit board can contribute to this goal. While using point-to-point wiring is certainly possible, the PCB

not only offers a consistent physical geometry and helps to prevent miswiring, but it allows a great deal of flexibility, as this PCB resembles a cross between a proto board and a typical PCB. Each board holds two tube sockets (four buffers) and many extra holes.

The flexibility is truly staggering. By reconfiguring the PCB, dozens of arrangements are possible, as 1st, 2nd, 3rd, and 4th order crossover slopes can be easily accommodated on this PCB. Two channels of matching high-pass and low-pass filters (up to 3rd order) fit on one board, as does a single channel's three-way crossover made up of 1st, 2nd, and 3rd order filters (three-way crossovers using fourth-order filter slopes require cascading boards).

But so much freedom can baffle: Which capacitor goes where? Which half of the tube the input? Unfortunately, the formulas and schematics needed to cover all the possible arrangements would fill this entire magazine. Consequently, a Windows software program was created to calculate both the component values and their placement on the PCB. A screendump of the program in action is shown in **Figure 1**. *Elektor's Tube Crossover Designer* program may be downloaded from this month's Free Downloads page at www.elektor-electronics.co.uk. The file number is **020297-11**.

The program covers fourteen basic filter configurations, which by cascading PCBs easily doubles the possible crossover configurations. Unlike many electrical engineering programs, it is easy to use: just key in the

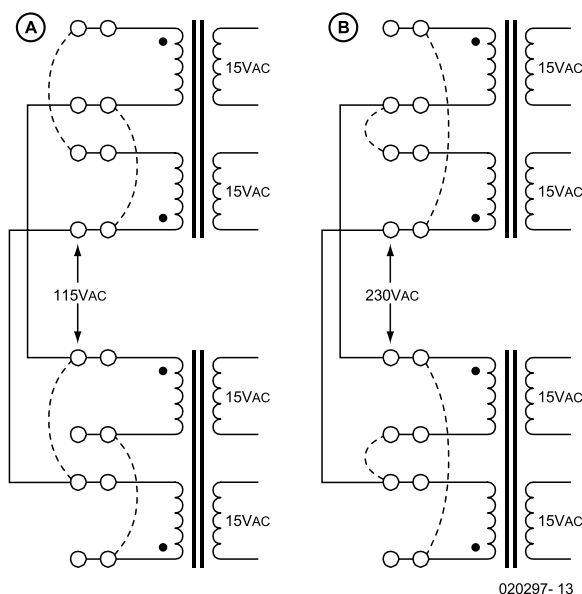


Figure 3. Mains transformer wiring for 115 VAC mains (Figure 3a) and 230 VAC mains (Figure 3b). The mains frequency (60 Hz or 50 Hz) is immaterial.

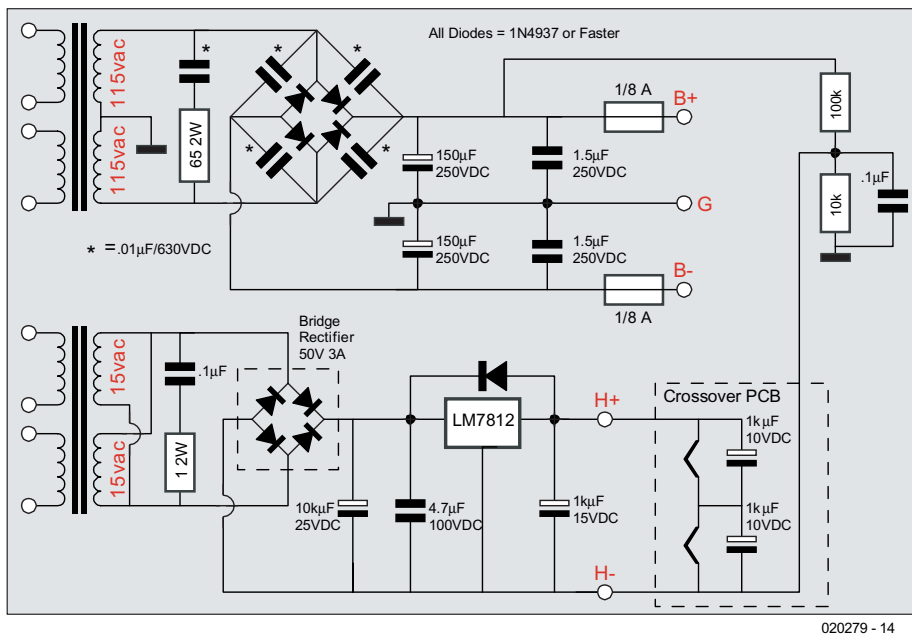


Figure 4. Circuit diagram of the power supply unit (PSU).

desired crossover frequency, the filter type (high-pass or low-pass), the filter order (1st, 3rd, or 4th), and the filter alignment (Bessel, Butterworth, or Linkwitz-Riley), the part values are displayed in a grid. Pressing the 'Schematic' and 'PCB' buttons toggles the view between the circuit's schematic and its part placement on the PCB.

The Circuit

This tube-based crossover, of which a randomly chosen variant is shown in **Figure 2**, makes use of cathode followers to offer both a low output impedance and a buffering of the crossover's tuning elements. Cathode followers provide no gain and little distortion, as all of the triode's potential gain is used as degenerative feedback to lower its output impedance and flatten its frequency response. Because the cathode follower's output follows its input in phase, its input capacitance is free of the Miller Effect. Additionally, the cathode follower allows the crossover's output to be recirculated into the filter network to create a positive feedback loop.

Many filter alignments need some positive feedback to eliminate the need for inductors within the network, and to compensate for the otherwise drooping output from a solely capacitive and resistive network at the transition frequency.

The crossover uses either 6DJ8 or 6N1P tubes (or any other dual triode that shares the same pinout and heater voltage and has a low R_p and high μ , e.g. 6BQ7, 6BS7, ECC85,

ECC88, 6DJ8, 6AQ8).

Referencing the cathode follower's input to ground sidesteps the need for additional input coupling capacitors. In fact, this circuit has been designed with a goal of eliminating as many coupling capacitors as possible. (While this also serves to cut the cost, the savings are somewhat offset by the need for a symmetrical power supply (± 165 volts), rather than the more conventional mono-polar power supply of most tube equipment).

Protective Diodes

One problem we face is that the power supply will come up to full voltage much more quickly than the triodes will begin to conduct. This means that at turn-on the triode's grid will see 0 volts and its cathode will see -165 volts. Such a large differential can damage the triode by 'cathode stripping', wherein pieces of cathode's surface are pulled away by the severely positive grid when the tube is still cold.

Adding a diode and zener in series solves this problem. When the triodes are hot, the pair of diodes do not conduct and are effectively out of the circuit. When the triodes are cold, they conduct, forcing the cathode to be only a safe -11 volts relative to the grid.

The power supply

The Signal IF-30-30 and IF-30-230 mains transformers used by the author are encased in plastic and are designed to be mounted on a printed circuit board. Both come with dual primaries, allowing use in countries that use either 115 VAC and 230 VAC. **Figure 3a** shows the layout for 115 VAC; **Figure 3b**, the layout for 230 VAC. The complete circuit diagram of the PSU appears in **Figure 4**. It is a simple affair. Two power transformers are used, one for the high-voltage bipolar power supply for the cathode followers and one for the low-voltage heaters.

Each transformer holds two secondary windings. The high-voltage portion of the power supply uses the two 115-VAC windings to create a centre-tapped full-wave bridge configuration that yields the positive and negative 165-volt rail voltages. Because the cathode follower does such a good job of rejecting power supply noise at its output, no regulation is used on these high-voltage rails. Instead, conventional RC filters are used.

The low-voltage heater power supply uses two windings to create full-wave centre-tapped configuration that yields the single positive rail voltage. This raw DC power supply then feeds a fixed 12-volt three-pin IC regulator. The tubes contain 6.3-volt heaters, which when placed in series across the 12-volt power supply see only 6 volts. This lower voltage is within acceptable voltage tolerances and will only serve to extend the tubes' lives.

Filter Alignments

In audio applications, the Butterworth filter is the most popular type. This makes sense, as it boasts a fairly flat time response, a fairly crisp transition shape and the flattest passband response. Its chief competitor, the Bessel filter, offers flatter time response, but not as sharp a transition shape nor as flat a passband response. Other filter alignments, such as the Chebyshev and the elliptic, are seldom used in audio because of undesirable characteristics such as ripple in the passband or sharp phase shifts.

On the other hand, odd order Butterworth filters (e.g. 1st and 3rd) exhibit an odd multiple of 45 degrees of phase shift (i.e. 45°, 135°, and 215°) per number of filter order at the transition frequency, which only gives rise to a +3 dB boost, which compensates perfectly

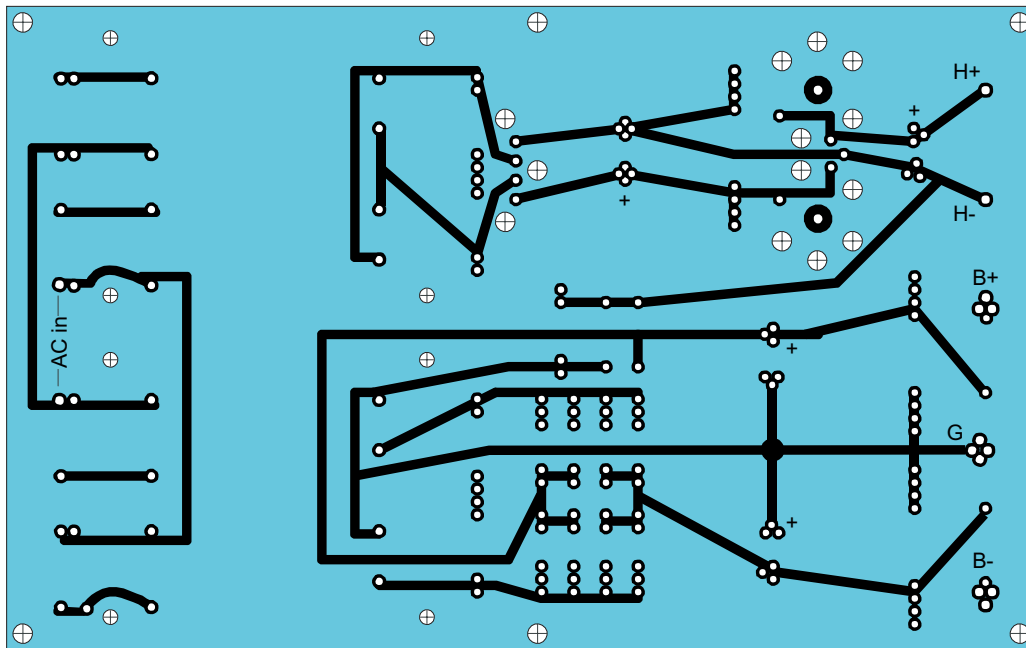


Figure 5. Copper track layout of PSU board (67% of true size).

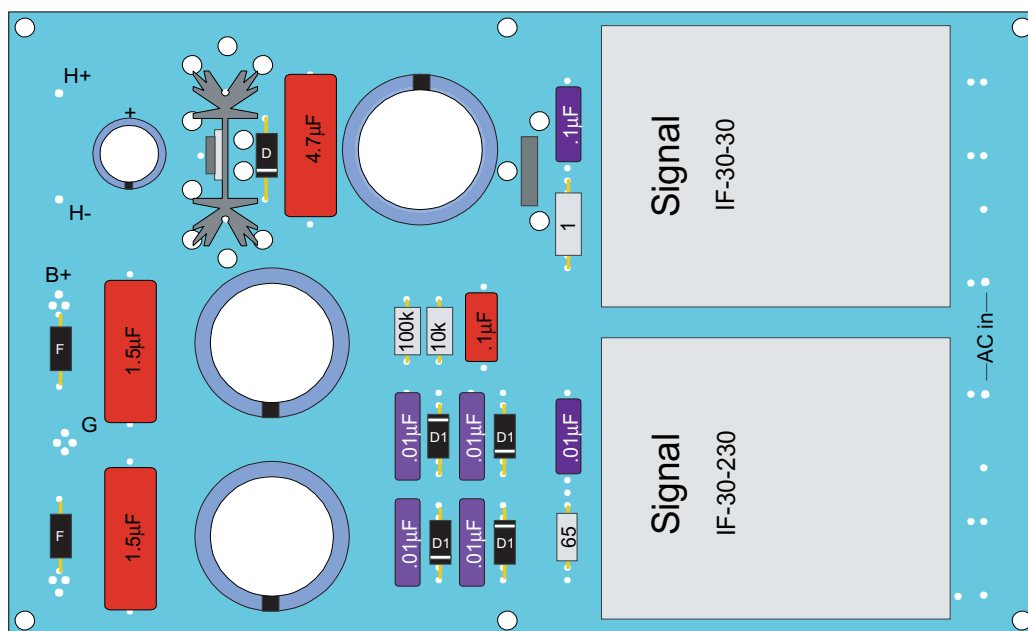


Figure 6. Component mounting plan of PSU board (67% of true size).

with the -3 dB dip in output at the crossover frequency. Thus the odd-order Butterworth filters sidestep the need for an adjustment in output amplitude.

In other words, making a flat even order crossover requires that the signal be not -3 dB, but -6 dB down at the crossover frequency, which the Linkwitz-Riley alignment provides for 2nd and 4th order crossovers. Still, experimentation is the best path. The advantage an active crossover enjoys is that experimentation is much more readily and cheaply done than with a passive crossover.

1st, 2nd, and 3rd Order Crossovers

The first-order crossover is at once the most trivial and the theoretically best crossover configuration, as this simple crossover offers the flattest phase and frequency summation at the transition frequency. Unfortunately, its shallow cutoff slopes often fail to protect fragile tweeters and they often fail to curb slow woofers from trying to reach too high. Moving up from two-way to three- or four-way crossovers eases the problem of potential damage to speakers as do robust high-quality (i.e., expensive) loudspeaker drivers.

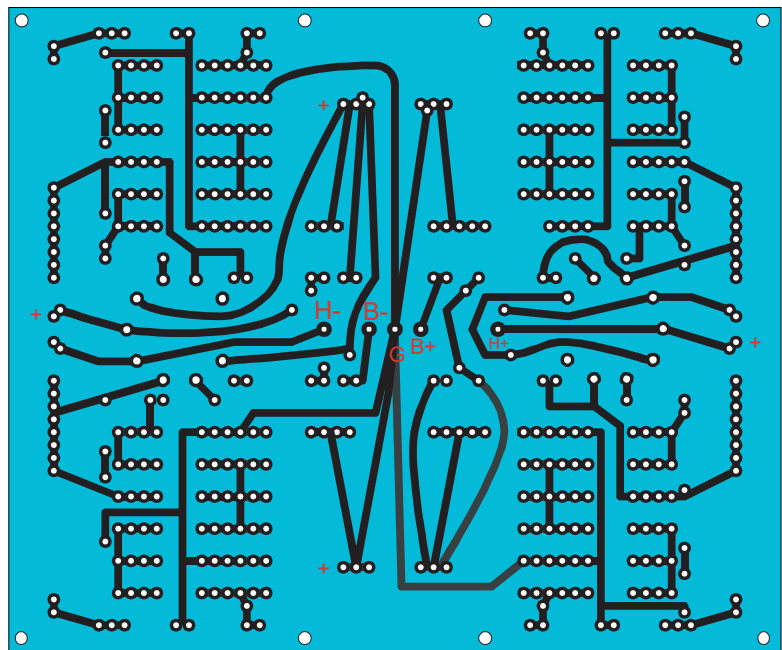
One point to bear in mind is that a first order filter can be used in conjunction with higher order filters. One particularly felicitous pairing is a first-order high-pass filter with a third-order low-pass filter. This combination works well with full-range loudspeakers and subwoofers. To realize this arrangement, as little as one PCB will be needed for stereo, if partially buffered filters are chosen.

In fact, the high-pass section's filter can be defined by its output capacitor working into the load presented by the following amplifier. While this would eliminate one coupling capacitor from the signal path, it would make the crossover less universal, as the output coupling capacitor would have to be changed to match different input impedances from different amplifiers. Furthermore, using two capacitors adds an additional protective high-pass filter at the low frequencies.

Two PCBs will be needed for fully buffered filters, however, as both the high-pass filter and the low-pass filter must be nested between two cathode followers.

Because of the phase differences in low and high outputs at the transition frequency, some experimentation will be needed to yield the best integration between subwoofer and satellite, with subwoofer's phase probably having to be reversed by reversing the speaker cable's plus/minus connections to the subwoofer.

As we move up in filter order, more



020297 - 17

Figure 7. Copper track layout of the multipurpose crossover board (67% of true size).

options become available. The 2nd- and 4th-order crossover can be given Bessel, Butterworth, and Linkwitz-Riley alignments. The 3rd-order crossover can be aligned to Bessel and Butterworth alignments, but not Linkwitz-Riley.

For all three alignments, the PCB may be used in two configurations: completely buffered and half-buffered. In completely buffered version the filter tuning elements are safely tucked between two cathode followers and one PCB will be needed per channel to provide up to 3rd-order filtering. Buffered 4th-order crossovers are not covered, as they would require an excessive number of PCBs. For example, a fully-buffered two-way, 4th-order crossover alone requires 12 cathode followers, i.e. 3 PCBs, which is the power supply's limit; while a fully-buffered three-way requires 16 cathode followers and 4 PCBs.

In the half-buffered version, although the output is buffered, the tuning elements connect directly to the signal source. Thus the assumption is that the filter will be fed from a low-impedance source, such as a line amplifier or CD player output, not a high-impedance source, such as a potentiometer.

Using the half-buffered version allows two channels of two-way crossovers (up to 3rd order) or one channel two-way 4th-order filters to be accommodated on one PCB. Three-way crossovers require cascading PCBs or using one PCB per channel for filters of up to 3rd order. While cascading two PCBs adds more active devices in the signal path, it does offer better attenuation of low frequency signals for the tweeter.

For example, given crossover frequencies of 500 Hz and 5 kHz (2nd order, 12 per dB octave filters), the first PCB splits the frequencies below 500 Hz off to the woofer and sends the frequencies above 500 Hz off to the second PCB, which then applies the 5 kHz split. The result is that the midrange sees 2nd-order slopes at 500 Hz and 5 kHz, while the tweeter sees a 2nd-order slope from 5 kHz down to 500 Hz and a 4th-order slope (-24 dB per octave) from 500 Hz down. This extra low-frequency filtering helps shield the tweeter from low frequencies and is particularly helpful with horn tweeters, as the normally high loading the horn provides to the diaphragm disappears at low frequencies.

Construction

The PCB artwork and component mounting plan of the PSU board are shown in **Figures 5 and 6** respectively. One power supply board can power up to three crossover PCBs. Both crossover and power supply PCBs can be housed in a single chassis or in separate enclosures. If the latter approach is adopted, an 'umbilical cord' will be needed, which for safety should be shielded and grounded; furthermore, it should end in a female termination (the crossover chassis holding the complementary male prongs) to prevent inquisitive fingers from touching the high-voltage connections.

The copper track layout of the general-purpose crossover board is shown in **Figure 7**. While the *Crossover Designer* program displays the layout on the crossover board(s) and the part values, a few guidelines are required. All the filter network defining resistors should be ½ watt and at least 2% tolerance; the filter network's capacitors, ≥ 160 VDC and at least 2% tolerance. The four cathode follower load resistors per crossover board should be 1-2 watt devices and should be mounted with a small gap (2-4 mm) between the

PCB and their bodies. The same holds true for the two 3250-ohm voltage-dropping resistors, which should be 2- to 5- watt devices.

The power supply PCB holds the power transformers and supporting circuitry. The power transformers are quite heavy and could easily be ripped from the PCB during a fall; thus, they should be both soldered and screwed to the PCB. Four #4 self-tapping screws per transformer (along with eight solder joints) will keep the transformer safely in place.

Unlike the crossover PCB, the power supply board offers only one optional wiring configuration: 115 or 230 VAC input. Shrouded wire should be used to create these and all other PCB jumpers.

Testing

The power supply board should be tested first without any external connections. A variac is recommended, it allows testing at lower, safer voltages.

The low-voltage portion of power supply should put out 12 VDC with no more than a ± 0.5 V error.

The plus and minus high-voltage portion of the power supply develop much greater voltages when

unloaded than when loaded: hence the need to overspecify capacitor voltages. Expect to see voltages closer to 200 volts than the expected 165 volts.

First test the crossover boards without the tubes; and then if all voltages are in line with expectations, test the board with the tubes in place. Because the heaters are in series, in the absence of the tubes no voltage will be present across the heater (4 & 5) of the tube socket. But across the two sockets, 12 volts should be measured. The plate voltage (pin 6) should exceed 165 volts and cathode voltages (pins 3 & 8) should be roughly -11 volts relative to ground. With the tubes in place, plate voltages for either tube should be close to 100 volts; the cathode voltages, +3 volts (the cathode resistor's large value effectively defines an autobias circuit in itself.)

Using the Crossover

Quite likely, the loudspeaker drivers will not match in efficiency, requiring an adjustment in crossover output level to achieve balance. A white noise generator and a soundlevel meter are needed for precise adjustment. Or you may choose to the following method: adjust the level until it sounds correct, then back off on the bass a tad.

If you have any questions or problems, email the author at crvquestion@glass-ware.com.

(020297-1)